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Two stages kinetics of municipal solid waste inoculation composting processes

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Abstract: In order to understand the key mechanisms of the composting processes, the municipal solid waste (MSW) composting processes were divided into two stages, and the characteristics of typical experimental scenarios from the viewpoint of microbial kinetics was analyzed. Through experimentation with advanced composting reactor under controlled composting conditions, several equations were worked out to simulate the degradation rate of the substrate. The equations showed that the degradation rate was controlled by concentration of microbes in the first stage. The degradation rates of substrates of inoculation Run A, B, C and Control composting systems were 13.61 g/(kg·h), 13.08 g/(kg·h), 15.671 g/(kg·h), and 10.5 g/(kg·h), respectively. The value of Run C is around 1.5 times higher than that of Control system. The decomposition rate of the second stage is controlled by concentration of substrate. Although the organic matter degradation rates were similar to all Runs, inoculation could reduce the values of the half velocity coefficient K_m and could be more efficient to make the composting stable. Particularly, for Run C, the degradation rate is high in the first stage, and K_m is low in the second stage. The results indicated that the inoculation was efficient for the composting processes.

Keywords: municipal solid waste; inoculation complex microbial community; oxygen consumption; two stages kinetics equations

Introduction

Composting is a nature process, but many man-induced innovative measures have been developed to accelerate composting efficiency. Various specialized seed inoculums have been applied for practical engineering (Biey, 2000). The microbial flora and the mass concentration of microbes in MSW composting processes underlying inoculation are different in various stages (Lei, 2000; Akihito, 1998). At the same time, the living environment of microorganisms is also incessantly changing due to the increase of metabolizing production and consumption of biochemical reaction. In the initial stage, the concentration of organic matter was high enough to be decomposed and the microbial mass could be the limited parameter. Thus, inoculation and increase the concentration of microbes to reasonable level is useful. With the process undergoing, the concentration of organic matter decreased gradually and the microbial mass increased at the same time, then the metabolic heat is not enough to maintain composting temperature, so the oxygen uptake rate decreased slowly. The composting process is becoming the second stage in which the concentration of substrate is limited parameter. Therefore, to examine the efficiency of inoculation, it is indispensable to follow the composting different stages. However, most of the existing systems are seldom considered the various stages of inoculation composting processes. Therefore, the present studies are difficult to be suitable for real composting processes to determine the efficiency of inoculation. Thus, it is necessary to consider the intrinsic rate equations with fundamental microbial kinetics to produce a dynamic model of the inoculation composting processes.

The main object of this study is to develop a more optimum method for estimating the seed effects which has not been suggested yet. Additionally, it will discuss which parameter could be mainly affected by seed inoculation among degradation rate. Furthermore, this paper will analyze the characters of typical experimental scenarios from the viewpoint of the two stages kinetics. Two comparable indexes including the maximum degradation rate and half velocity coefficient were investigated to estimate the effect of seed various inoculums on the degradation rate of MSW during composting.

1 Materials and methods

1.1 Composting materials and equipment

MSW from a typical community in Beijing (China) were collected, sorted and mixed directly with sawdust without drying. The original MSW mater content was around 60%. The moisture contents of the initial waste mixtures of all tests were adjusted to around 55% by introducing some amount of

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water or bulking agent to the mixture. The carbon to nitrogen (C/N) ratio was around 24:1. Inoculums A, B and C of aqueous medium were introduced to each reactor immediately before the temperature recording. The amounts of Inoculums A, B and C added to reactor were 2% of wet mixture weight. The Inoculum A used in this experiment was made by mixing microorganisms having substantial activity on easily biodegradation organic substrates, such as *Bacillus azotofixams*, *Bacillus megaterium* and *Bacillus mucilaginosus*. Inoculum B was made by mixing effective cellulolytic strains(i.e. *Trichoderma koningii*, *Streptomyces cellulosae*, etc.) and White-rot fungi. Inoculum C was made by mixing Inoculum A and B. The inoculum had various microorganisms as shown in Table 1.

Table 1 Characteristics of seed inoculums

Microorganisms		Inoculum A	Inoculum B	Inoculum C
Bacteria	CFU(30℃ growth)	2.5×10^{11}	1.6×10^{7}	1.8×10^{11}
	CFU(60℃ growth)	6.3×10^{9}	7.5×10^{8}	5.6×10^{9}
Fungi	CFU(30℃ growth)	ND	1.5×10^{6}	1.2×10^{6}
Actinomycetes	CFU(60℃ growth)	ND	5.6×10^{9}	4.5×10^{9}

Notes: CFU. colony forming unit(CFU/ml medium); ND. not detected

1.2 Composting method

Composting reactor system which was designed as heat-controlled and on-site detecting in-vessel is shown in Fig. 1 and Fig. 2. Air was introduced to the reactor through a flow meter and a perforated PVC tube placed below a fine mesh screen. The reactors were placed at room temperature. Precise solid wastes temperature sensors and a data logger were used for temperature measurements. The exhaust gas from the reactor was put into two analyzers, one is an O_2-H_2S monitoring instrument (Model MD-520E), and the other is CO_2 analyzer (Model LX-710). The CO_2 concentration was recorded continuously, while O_2-H_2S concentration of gas in the compost was analyzed every four hours. The composting materials were manually turned-over and sampled once daily. The composting weight and moisture content (MC) were determined everyday, among which the MC were measured and adjusted by sawdust mixing or distilled water addition to maintain the optimal range around 55% (Xi, 2002).

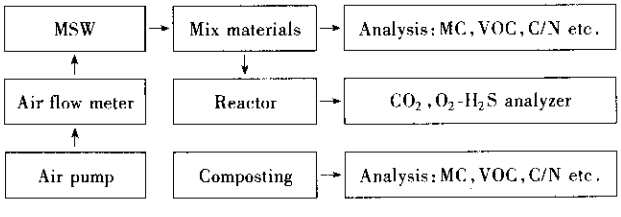

Fig. 1 Schematic diagram of experimental system

1.3 Chemical and biological analyses and calculation

1.3.1 Chemical and biological analysis

Samples were taken from approximately six sites of the reactor, and then they were assembled, mixed and sieved through a 4 mm mesh screen. Dry matter content was analyzed with parallel samples at 105℃ for 12 h.

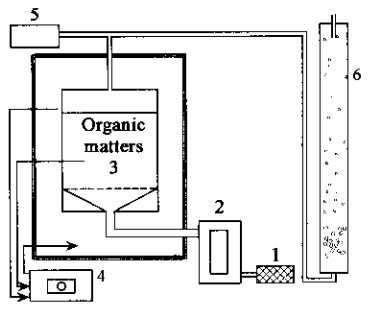

Fig. 2 Schematic diagram of experimental reactor
1. gas pump; 2. gas flow meter; 3. composting tank; 4. temperature maintainence box; 5. gas analyzer; 6. filter

TN, TOC and pH were determined in water extracted (1:5 by volume) from samples after shaking for 2 h. TN in the mixtures was measured by the Kjeldahl method and samples were pretreated with sulfuric acid. TOC was measured by the standard method.

The number of microorganisms was determined with plate counting method as described by Strom(Peter, 1985). Actinomycetes, and fungi were isolated on the agar plates by dilution plating. Mesophilic and thermophilic microbial strains were obtained by plating samples taken from composting processes in cultivating the plates at 30 and 60℃ respectively. Mesophiles and thermophiles were isolated and maintained on trytone soy agar(TSA) and peptone agar(PA) respectively. Isolates were obtained by streaking out all the colonies of a spread plate within a sector containing 40 colonies.

1.3.2 Chemical and biological calculation

(1) The oxygen uptake rate can be calculated by Eq. (1)

$$R = \frac{q\cdot(z_i - z_e)}{V_M M_d}. \qquad (1)$$

Where R is the oxygen uptake rate(mol/(h·kg)); q is the airflow(m^3/h); z_e is O_2 concentration of outlet gas; z_i is O_2 concentration of inlet gas; V_M is the volume of per mol gas (m^3/mol); M_d is the weight of dry matter.

The degradation rate of organic matter was calculated through Eq.(2):

$$V = \frac{M_d R A_0}{aS}. \qquad (2)$$

Where V is the organic matter degradation rate(g/(kg·h)); a is the oxygen uptake quantity of per unit organic matter degradation (1.27 kg/kg); A_0 is the molecular weight of oxygen(0.032 kg/mol); R is the oxygen uptake rate; S is the substrate concentration(kg).

(2) CO_2 conversion rate calculation

$$\Delta CO_2 = \int_0^t Z'_C q\,dt. \qquad (3)$$

Where Z'_C is CO_2 concentration of outlet gas; t is the composting time.

$$r_{CO_2} = \Delta_{CO_2} / W = \frac{\Delta_{CO_2}}{[W_0 - Y_{VM/CO_2} \int qZ'_C dt - \sum_{i=1}^{i} W_{Si}} , \quad (4)$$

$$W = W_0 - Y_{VM/CO_2} \int_0^t qZ'_C dt - \sum_{i=1}^{i} W_{Si} . \quad (5)$$

Where r_{CO_2} is CO_2 conversion rate (mol/(h·kg)); W is the dry matter weight in the reactor; W_0 is the initial dry matter weight in the reactor; Y_{VM} is the yield coefficient; W_{Si} is the sample weight of different time.

2 Results and discussion

2.1 Results

2.1.1 Emission of outlet gas

O_2, CO_2 and H_2S evolution have been used to measure decomposition rates for composting processes performed under different treatments(Eklind, 2000). When aeration flow was 1.0 l/(min·kg), the moisture of composting matters was around 55%. The oxygen(% O_2), carbon dioxide(% CO_2) concentration and H_2S concentration in outlet gas are shown in Table 2.

Table 2 Emission of gas in outlet

Time, d	Emission of oxygen, % O_2				Emission of carbon dioxide, % CO_2				Emission of H_2S, ppm			
	Control	Run A	Run B	Run C	Control	Run A	Run B	Run C	Control	Run A	Run B	Run C
0	20.9	20.9	20.9	20.9	0	0	0	0	0	0	0	0
24	20.2	14.2	16.2	14.3	0.7	5.4	4.18	5.8	0	0	0.5	1.0
48	17.2	10.4	13.4	11.9	3.36	3.18	6.85	9.82	0	0.3	1.0	4.0
72	15.9	7.83	10.4	8.2	4.5	11.9	9.50	11.1	30	10	5	3.2
96	14.5	16.8	15.8	14.2	5.82	3.71	6.01	6.5	28	8.2	4.8	2.8
120	12.6	19.0	17.9	17.3	7.55	1.82	2.91	2.75	20	6.5	3.3	1.9
144	18.1	20.7	20.1	19.6	2.92	0.64	0.55	1.30	15.4	4.3	2.0	0.5
168	20.2	20.8	20.8	20.7	1.20	0.54	0.45	0.27	12.1	2.2	1.0	0.2
192	20.6	20.9	20.8	20.8	0.74	0.41	0.36	0.18	7.4	1.1	0.4	0
216	20.7	20.9	20.9	20.9	0.56	0.03	0.35	0.1	2.3	0.5	0.1	0
240	20.8	20.9	20.9	20.9	0.1	0.00	0.05	0.03	0.6	0	0	0
264	20.9	20.9	20.9	20.9	0.00	0			0	0	0	0

Table 2 indicated that carbon dioxide (% CO_2) concentration and oxygen (% O_2) have a good correlation during composting:

$$(\%O_2) = 20.9 — 1.1\ (\%CO_2).$$

Oxygen uptake rate results for the four experiments are presented in Fig. 3. The maximum oxygen uptake rate and total accumulate quantity in Control, Run A, Run B, and Run C were 0.22 mol/(h·kg) and 511.18 g/(h·kg), 0.32 mol/(h·kg) and 684.57 g/(h·kg); 0.28 mol/(h·kg) and 659.74 g/(h·kg); 0.34 mol/(h·kg) and 778.47g/(h·kg), respectively. It indicated that the highest oxygen uptake rate appeared in Run C and total O_2 depletion levels are as follows: Run C > Run A > Run B > Control. These results suggested that inoculation not only improve the rate of MSW, but also can improve the overall level of decomposition.

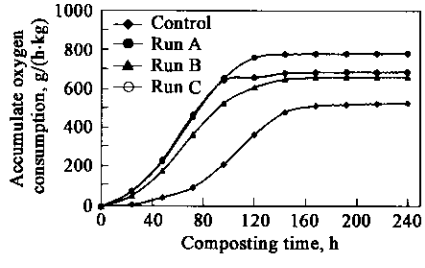

Fig. 3 Oxygen accumulate profile during the composting processes

The CO_2 concentration in the compost was found to be sensitive to seed inoculums(Fig. 4), carbon dioxide(% CO_2) concentration in Run C was more than that in control. The rate of carbon dioxide generation reached up to 0.30 mol/(h·kg) in Run C. However, the peak rate of carbon dioxide only 0.20 mol/(h·kg) in control. Since CO_2 conversation rate can be considered an indicator of the respiratory activity of the compost micro flora, the results suggested that biological activity was the highest in Run C and was the lowest in control.

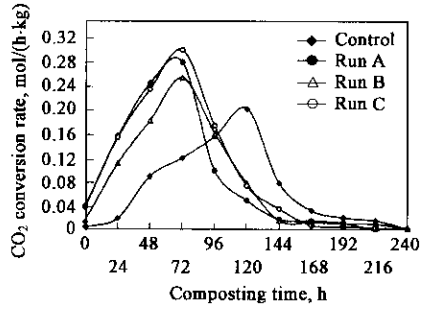

Fig. 4 CO_2 conversion rate profile during the composting processes

The concentration of H_2S in control system was high during composting processes. The maximal emission of H_2S was 0.456 mg/L, 0.152 mg/L, 0.076 mg/L, and 0.061 mg/L during Control, Run A, B and C, respectively. Next to this the H_2S-emission during Control system was not completely finished after 14 d period. In accordance to the results, inoculation is useful to control H_2S-emission.

2.1.2 Total heterotroph counts

To study the impact of different inoculums in composting

processes, total heterotroph counts in composting system were examined. As shown in Fig.5. CFU means colony form unit.

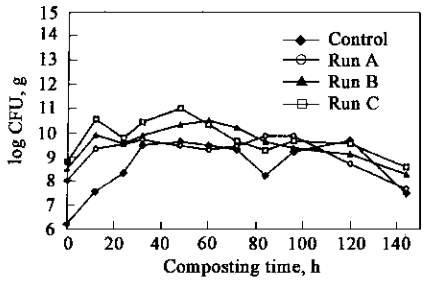

Fig.5 Total heterotroph counts profile in composting

A clear difference was observed between control and three inoculation runs. The population of total aerobic microorganisms of Run A, B and C were at a high level, the $\log_{10}$CFU(colony forming units) g^{-1} were from 8.0 to 10.0 at the onset beginning of the composting period(Fig.5). The microorganisms in Run A reached a peak time with $\log_{10}$CFU equal to 10 at day 2, Run B equal to 9.5 at day 4, Run C equal to 10 at day 3, and control equal to 9.0 at day 7, respectively. These met with the temperature profile.

2.2 Discussion

The self-heating that takes place is due to heat liberation from microbial metabolic activity. At the beginning of composting processes, the concentration of organic matter was high enough to be decomposed and the microbial population is could limit the overall process kinetics. Thus, inoculation and increase the concentration of microbes to propriety level is useful. With the process undergoing, the concentration of organic matter decreased gradually and the microbial population increase, then the metabolic heat was not enough to maintain composting temperature and oxygen uptake rate decreased. To examine the efficiency of inoculation, the composting processes were divided into two stages and the intrinsic rate equations with fundamental microbial kinetics to produce a dynamic model of the inoculation composting processes.

In the initial stage of composting from beginning to the peak of oxygen uptake rate, was controlled by concentration of microbes. The second stage from the peak oxygen uptake rate to the end was controlled by concentration of substrate. With this method, it was possible to describe the composting rate and microbial activity clearly, and it was also a good measure of simulation for the validation of the experimental data(Shin, 1999).

2.2.1 The first stage microbial kinetics

In order to understand the key mechanisms of the composting processes with inoculation and control, the paper analyzed four typical experimental scenarios at Control and Run A, B and C from the viewpoint of microbial kinetics.

In the first stage, a simple equation can be applied to simulate the degradation rate of the substrate which can be shown as a function of the microbial concentration for a heterogeneous system with solid substrate as follows(Haug, 1993):

$$v = -\frac{ds}{dt} = \frac{KA_v X}{K_X + X}, \tag{6}$$

where ds/dt is the rate of hydrolysis of solid substrate; k is the maximum rate of solid substrate hydrolysis which occurs at high microbial concentration; K_X is the half velocity coefficient equal to the microbial concentration when $ds/dt = v/2$. A_v is the available surface area per unit volume.

From Eq.(1), we have

$$\frac{1}{v} = \frac{K_X}{kA_v}\cdot\frac{1}{X} + \frac{1}{kA_v} = \frac{K_X}{V_m}\cdot\frac{1}{X} + \frac{1}{V_m}. \tag{7}$$

The equations of the first stage of kinetics on decompositions of inoculation Run A, B, C and Control derived from Fig.6 are as follows:

$$V_{\text{Run A}} = \frac{13.61X}{5.403 + X}; \tag{8}$$

$$V_{\text{Run B}} = \frac{13.038X}{5.63 + X}; \tag{9}$$

$$V_{\text{Run C}} = \frac{15.67X}{4.41 + X}; \tag{10}$$

$$V_{\text{Control}} = \frac{10.504X}{4.21 + X}. \tag{11}$$

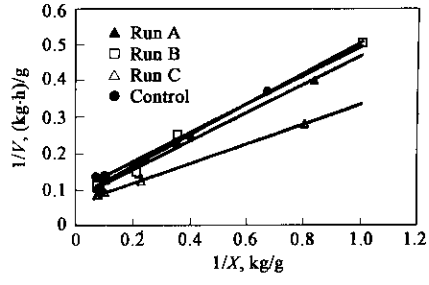

Fig.6 [1/V] vs.[1/X] in the first stage kinetic analysis

2.2.2 The second stage

In the second stage, the degradation rate of the substrate hydrolysis can be described as a function of the substrate concentration given as

$$V = \frac{V_m S}{K_m + S}; \tag{12}$$

$$\frac{1}{V} = \frac{K_m}{V_m}\cdot\frac{1}{S} + \frac{1}{V_m}. \tag{13}$$

From Fig.7, the second stage kinetic equations of Run A, B, C and Control were gained as follows:

$$V_{\text{Run A}} = \frac{7.73S}{204.95 + S}; \tag{14}$$

$$V_{\text{Run B}} = \frac{7.65S}{186.41 + S}; \tag{15}$$

$$V_{\text{Run C}} = \frac{7.26S}{154.25 + S}; \tag{16}$$

$$V_{\text{Control}} = \frac{7.71S}{214.18 + S}. \tag{17}$$

Although, most organic wastes were decomposed through bioactivity of the indigenous microbial flora(Control system)

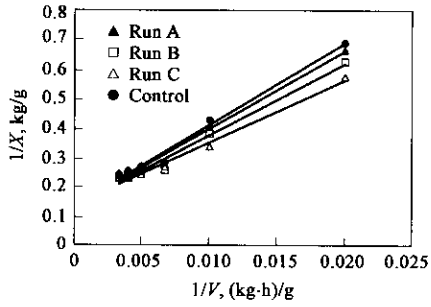

Fig.7 [1/V] vs. [1/X] in the first stage kinetic analysis

(Tuomela, 2000), this does not mean that the mass concentration of microbes is not limiting, particularly in the initial stage of the composting processes in which the concentration of indigenous microbes is low(Haug, 1993). Referring to Equation (8) to (11), increasing the microbial concentration(X) must increase the rate of decomposition except $X \gg K_s$. It was obvious that the seed inoculation could enhance the composting rate, for one reason is that it can increase the mass concentration of microbes; additionally, inoculation complex microorganisms which have high bioactivity for decomposing organic matter could enhance maximum degradation rates KA_v, which were 13.61 g/(kg·h), 13.08 g/(kg·h), 15.671 g/(kg·h), and 10.5 g/(kg·h), in Run A, B, C and Control systems respectively. In Run C, the seed inoculum C which was mixing inoculum A and inoculum B had a sufficient amount of variety of microbial activities for substrates. The maximum degradation rate in Run C of organic matter V_m in the first stage was around 1.5 times greater than the value of Control. Another function of inoculation was avoiding the lag periods of traditional composting processes. In fact, lag phase was often observed at the initial stage of batch composting operations where produce a quantity of odorous gas such H_2S, NH_3. Certainly the lag time could also be caused by other factors such as high moisture content, oxygen availability, low temperatures. However, if inoculation proper microorganisms into waste materials without enough indigenous microbial mass should increase the kinetics and avoid the lag time according Eqs. (8) to (11).

As discussed above, rates of reaction is not be limited by substrate in the first stage of composting, but with the composting processes undergoing, the solubilization of the solid waste is lower and lower and may be a significant rate controlling mechanism during the second composting stage. In this stage, after easily bio-decomposition organic matter disappearing, although the microbial concentration is high enough for decomposition of organic matter, which are likely contain most solids resistant to hydrolytic enzymes, such as cellulose fiber and lignin the solubilized organic matter which is limited and has resisted hydrolytic attack in composting reactor. Thus KA_v which is the same mean with V_m in equation $V = V_m S/(K_m + S)$. The V_m in Run A, B, C and Control is 7.73 g/(kg·h), 7.65 g/(kg·h), 7.26 g/(kg·h) and 7.71 g/(kg·h), respectively. Which is smaller than that in the first stage. Therefore, curing will require a considerable period time whatever in inoculation system or non-inoculation system. However, from the Eqs. (14) to (17), inoculation could reduce the value of the half velocity coefficient K_m which is 204.95 g/kg, 186.41 g/kg, 154.25 g/kg and 214.18 g/kg in Run A, B, C and Control system, respectively. Indeed, values of K_m likely mean the level of stability of the composting products. The lower the value of K_m, the more stable of the composting. Thus, Eqs. (14) to (17) indicated that inoculation complex microorganisms which contain cellulolytic strains, white-rot fungi such as in Run B and Run C was more efficient to make the composting stable. Particularly, in Run C it not only has high decomposition rate in first stage, but also K_m is low in the second stage. Thus, seed inoculum which contain easily biodegradation organic substrates microorganisms, such as *Bacillus azotofixams*, *Bacillus megaterium* and *Bacillus mucilaginosus*, as well as cellulolytic strains, white-rot fungi is necessary to avoid decomposition limitation, reduce emission odour gas and make the composting more stable.

3 Conclusions

It was evident that the inoculation could enhance the composting rate, control emission of odour gas and made the composting more stable. In the first stage, the decomposition rate of Run C was 1.5 times higher than in non-inoculation Control system. In the second stage, inoculation could reduce the value of the half velocity coefficient K_m, make the composting products more stable and improve the composting quality. Thus, seed inoculum C is necessary to enhance the efficiency of composting.

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